Introduction to RF/Radar Hardware and Architecture

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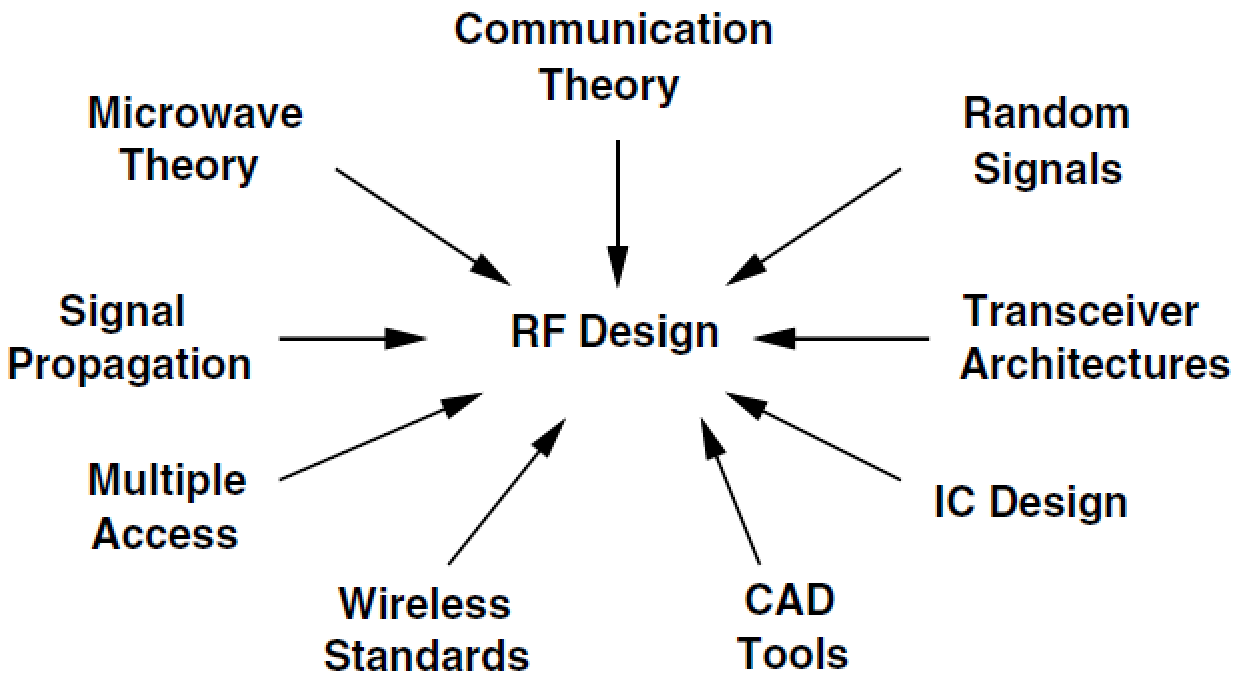
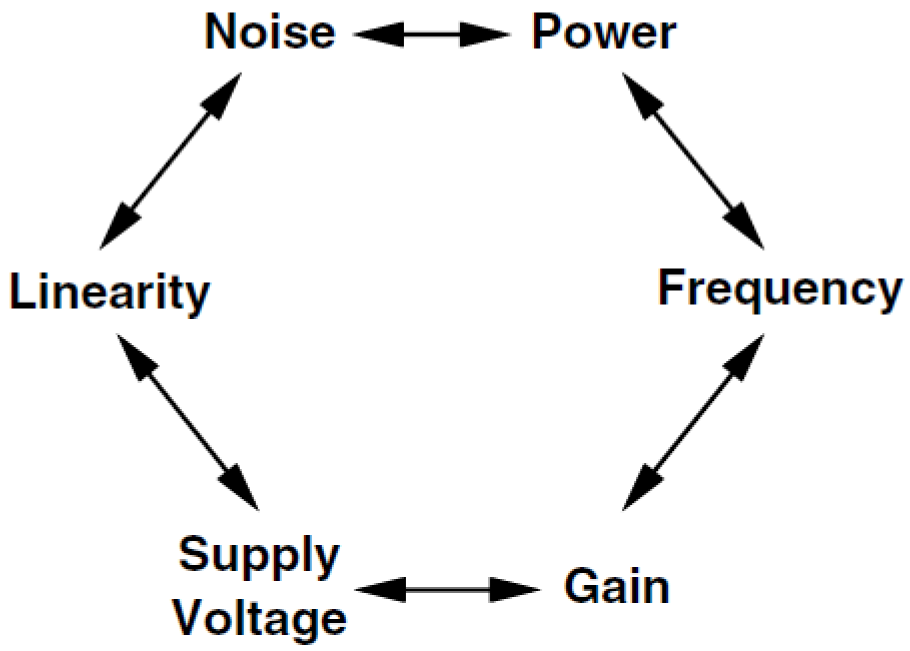
Radar ICs is part of RF Design



Everything is About Design Trade-offs



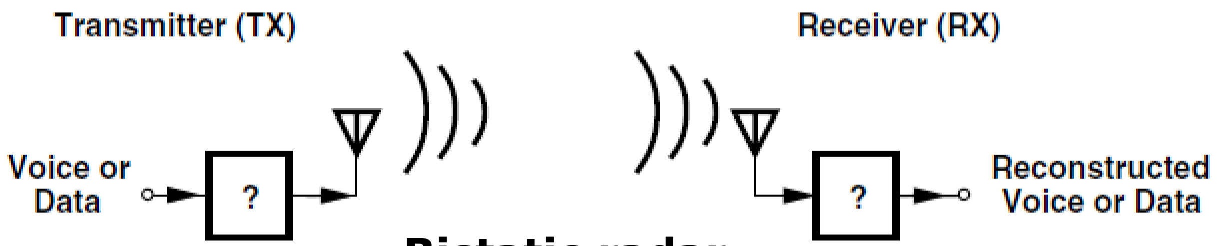
Outline

- RF hardware architecture
- Radar block diagram
- Fundamental antenna concepts
- Phased array antennas
- Power, noise and compression
- Next – How to pick the correct radar module?

- We are only talk about **high-level topics**, if you want to learn more…
  - 18-727 Board-level system design
  - 18-723 RFIC design
  - 18-758 Wireless Communications

Big picture

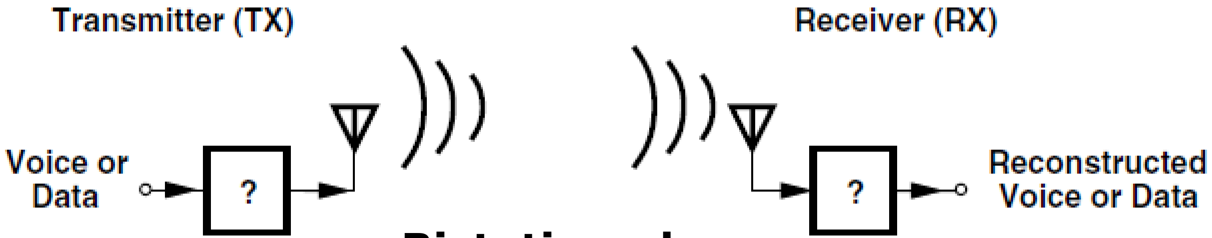
- Bistatic vs. Monostatic



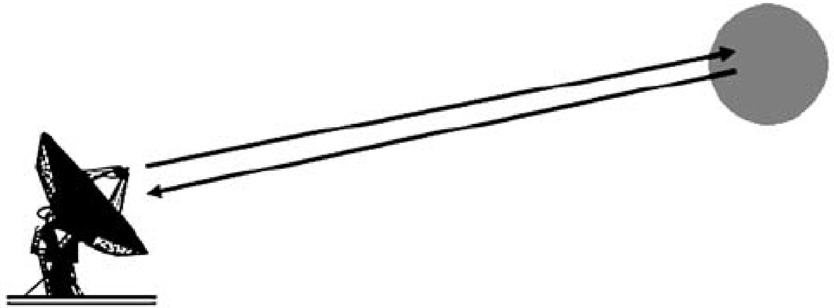
Bistatic radar

Big picture

- Bistatic vs. Monostatic

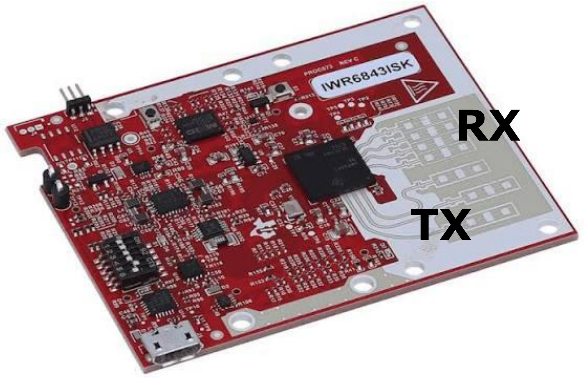


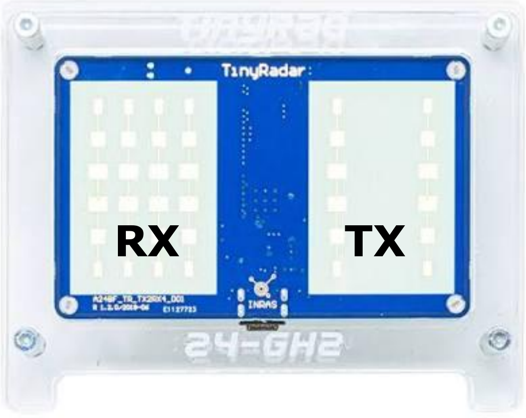
Bistatic radar



transmitter & receiver

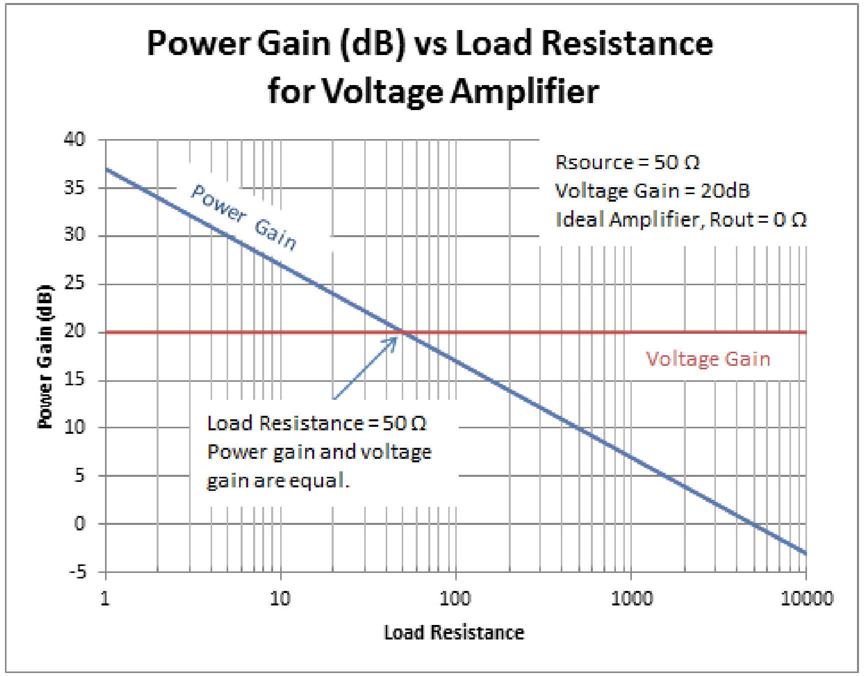
monostatic radar





Units Matter in RF Design

- The difference in voltage and power gain (dB)
- These two quantities are equal (in dB) only if the input and output voltages appear across ***equal impedances***

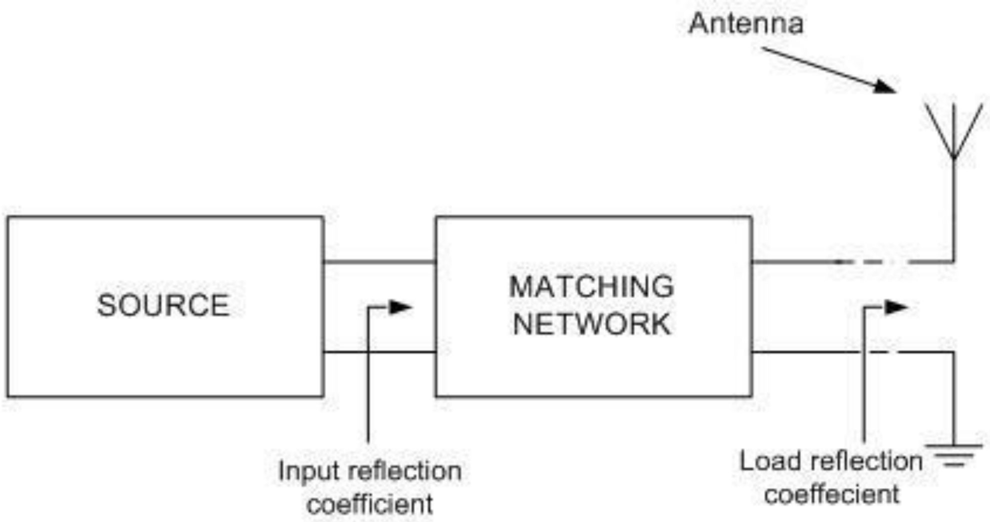


$$A_V|_{\text{dB}} = 20 \log \frac{V_{out}}{V_{in}}$$

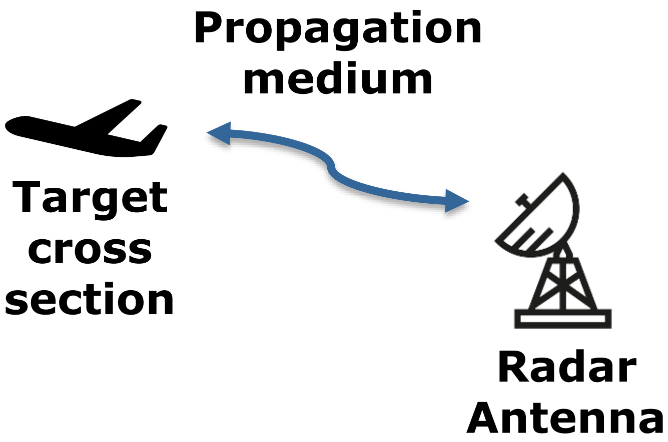
$$A_P|_{\text{dB}} = 10 \log \frac{P_{out}}{P_{in}}.$$

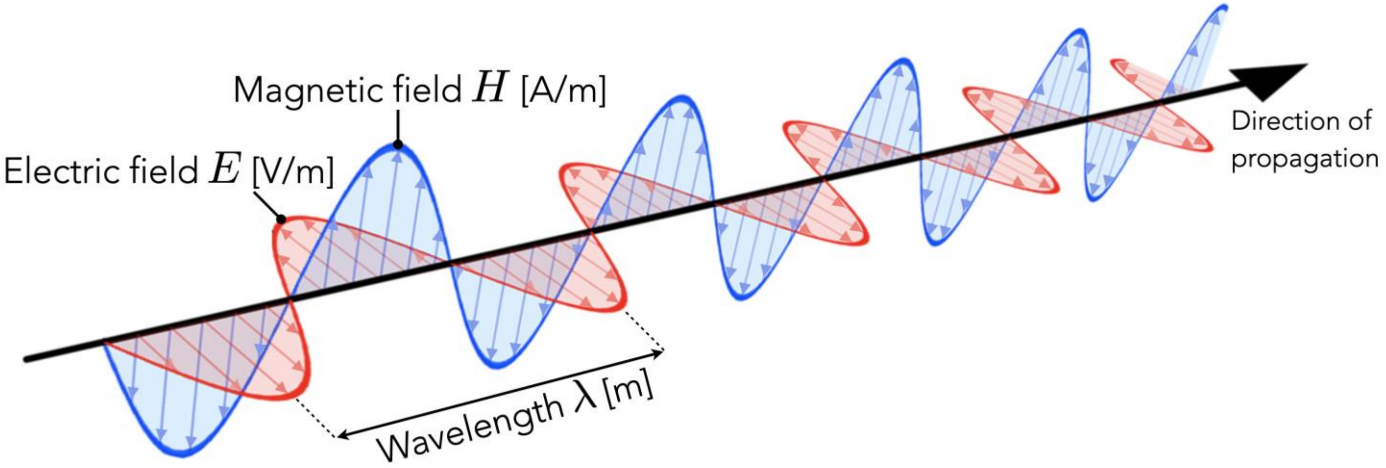
Impedance Matching

- Why? – It controls how much signal power send from the source to circuits
- Modern RF design agrees on 50 ohm as a typical impedance
  - This number has no specific meaning but just a mutual agreement!



Hardware - backbone to shape signals





Radar is a sensor that uses RF electromagnetic waves

- **Target properties** – reflectivity (radar cross section)
- **Radar characteristics** – transmitter power, antenna aperture, sampling rate
- **Propagation medium** – line-of-sight or occlusion, atmospheric attenuation

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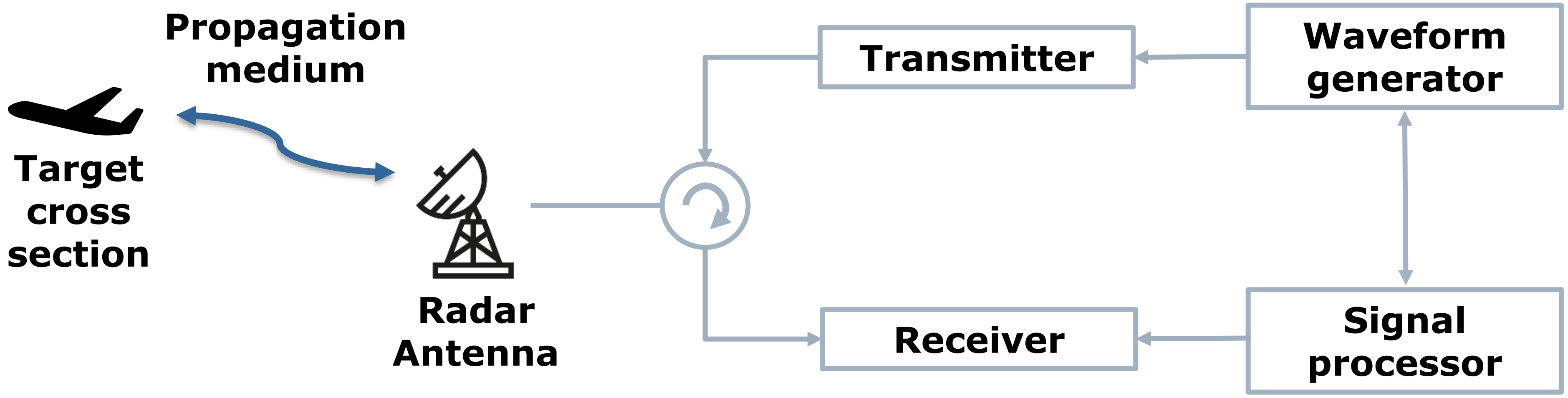
Radar Block Diagram

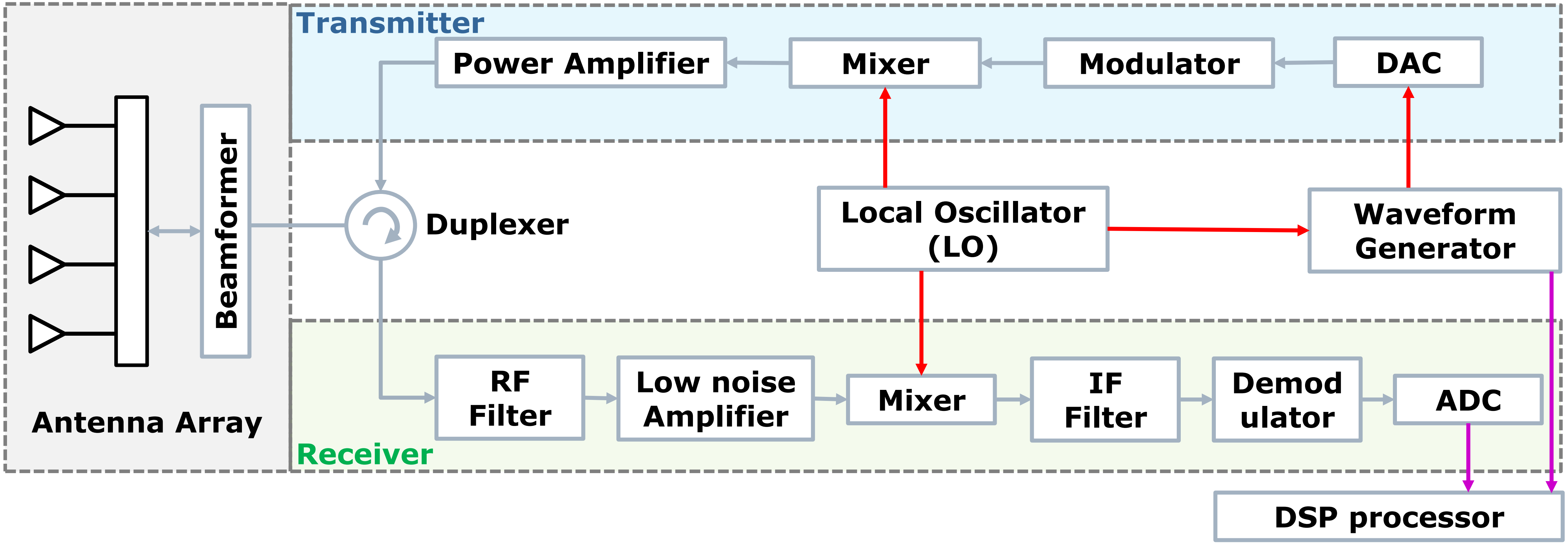


A minimal radar signal chain

- Waveform generation
- Transmitter receiver front-ends
- DSP modules

Radar essential RF components

- Typical radar system
  - Simple block diagram, real radar systems vary based on modulation and design



Frequency and Bandwidth

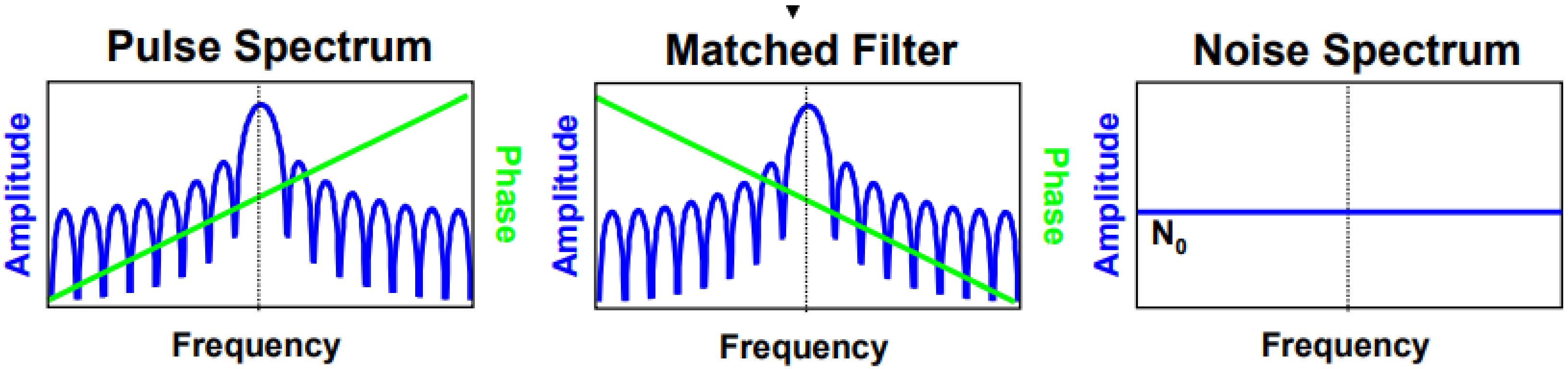
- Carrier frequency
- Chirp bandwidth and resolution
- IF bandwidth
- Sampling rate

Motivation of modulation and pulses

- A long pulse can have the same bandwidth (resolution) as a short pulse if the long pulse is modulated in frequency or phase
- Recap – we discussed Linear frequency modulation
  - Will discuss more on the trade-offs later

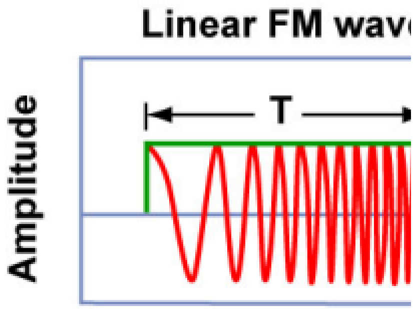
Matched Filter

- A long pulse can have the same bandwidth (resolution) as a short pulse if the long pulse is modulated in frequency or phase
- Matched filter is implemented by "convolving"

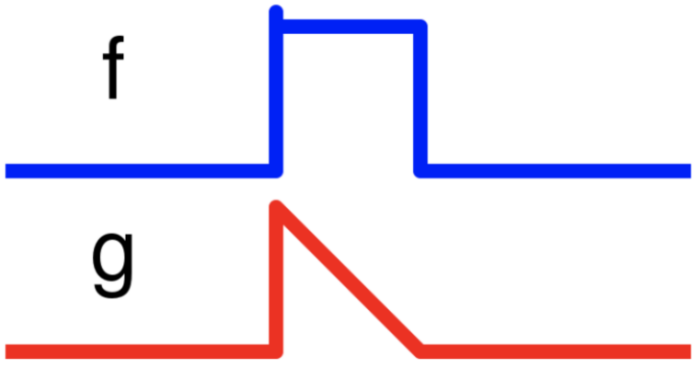


Linear FM Pulse Compression

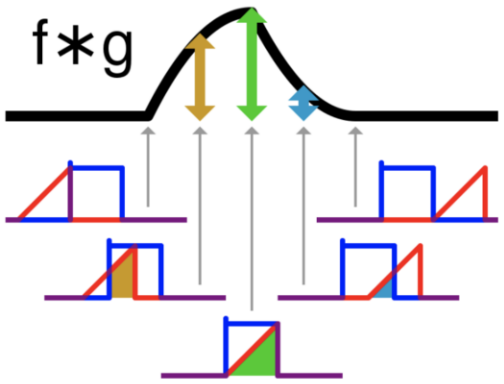
- Coupling range and Doppler velocity measurements
- Pulse compression and filter design matters
  - Why?



Example functions



Convolution operation result



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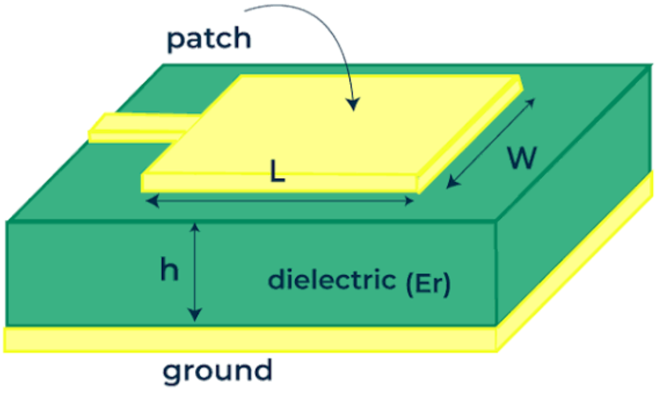
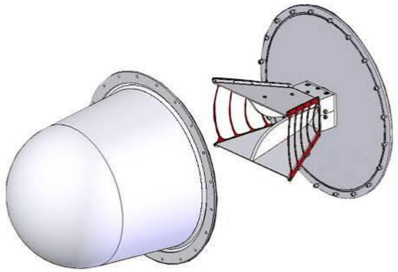
Antenna Characteristics

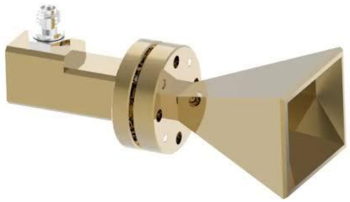
- Frequency
- Gain and Radiation Pattern
- Impedance and Voltage Standing Wave Ratio (VSWR)
  - Determine RF power ratio transmitted
- Polarization
- Far-field vs. Near-Field

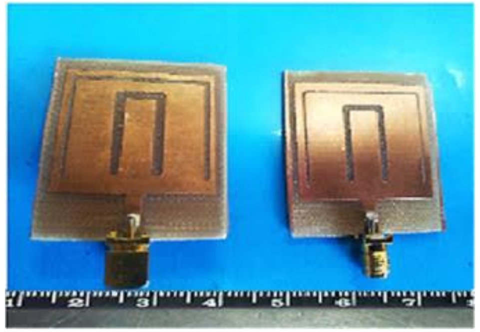
Common Radar Antenna Types

- Simple Patch Antenna
- Parabolic Reflector (Dish) Antenna
- Enclosed Radome Marine Antenna
- Horn Antenna
- Slot Antenna
- Phased Array



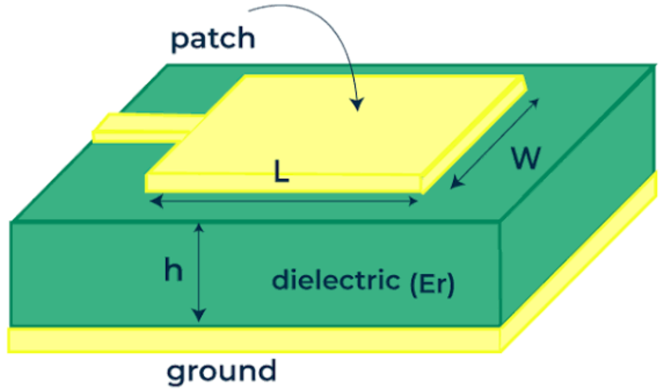






Patch Antenna

- It doesn't have to be a simple rectangle



Rule of thumb is sub-wavelength width

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}} \qquad L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}}$$

Patch Antenna –TI 77GHz Microstrip Patch

- Phased array – spacing matters
- Electromagnetic tools to simulate beampattern

2.7 *Antenna*

The BoosterPack includes onboard-etched antennas for the four receivers and three transmitters that enable tracking multiple objects with their distance and angle information. This antenna design enables estimation of distance and elevation angle that enables object detection in a three-dimensional plane. Figure 10 shows the PCB antennas.

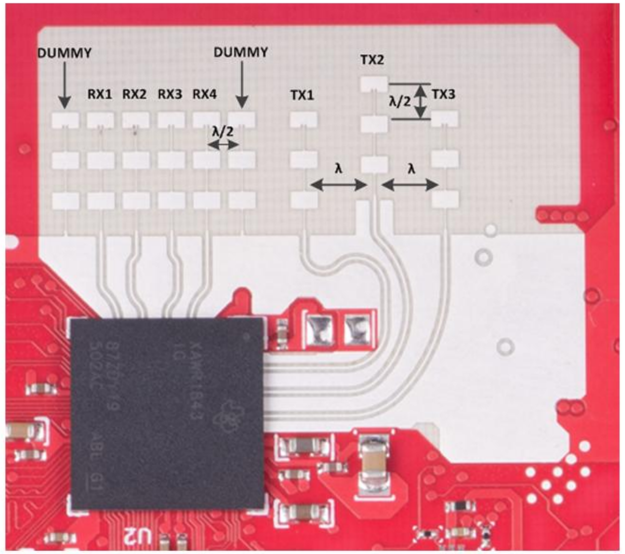
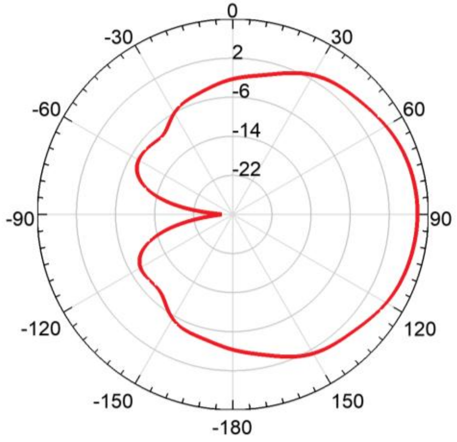
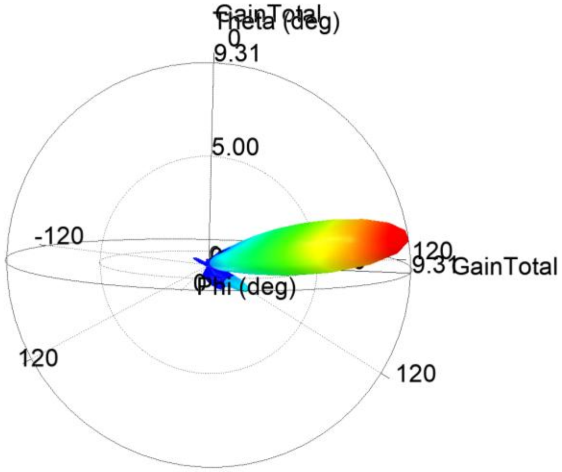


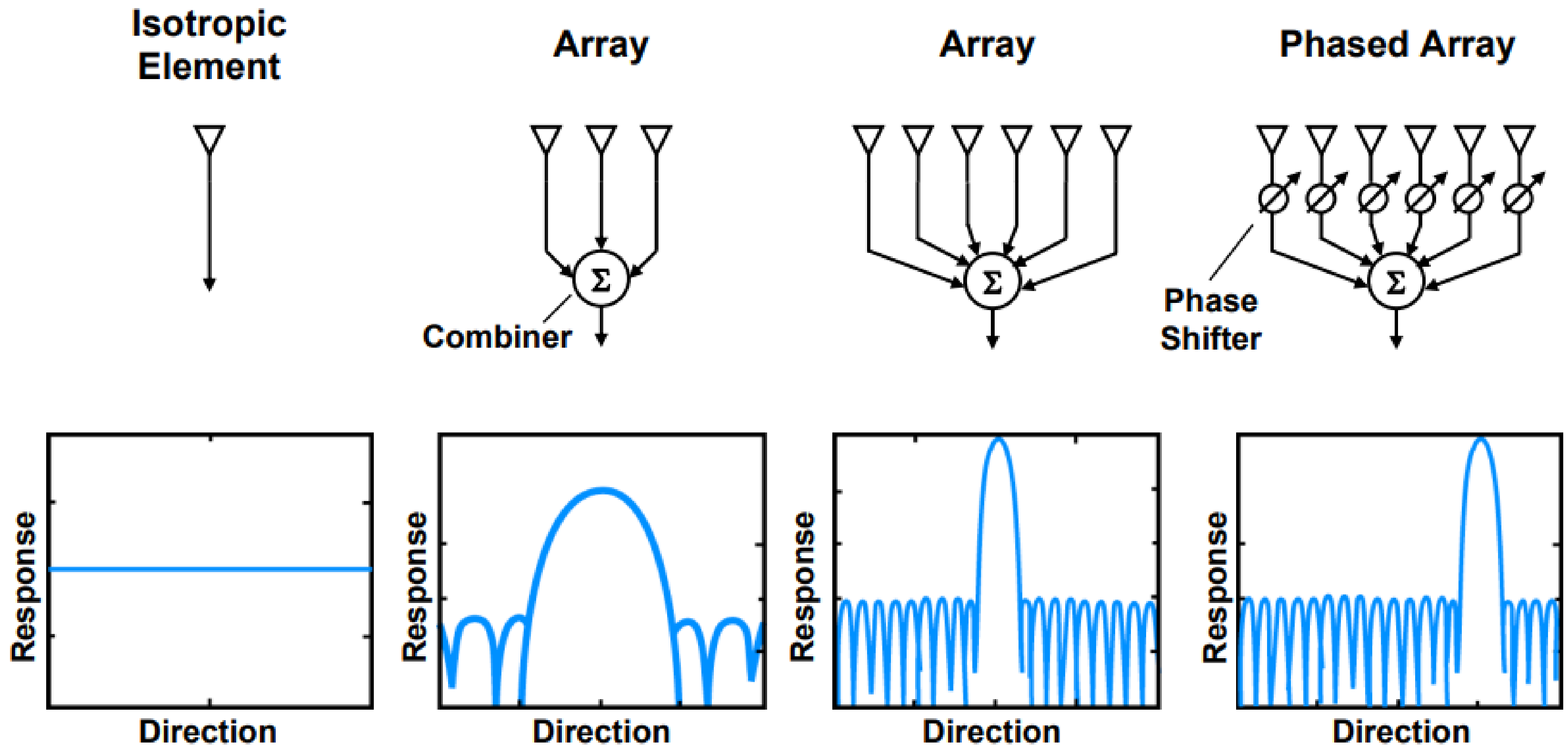
Figure 10. RX and TX Antennas





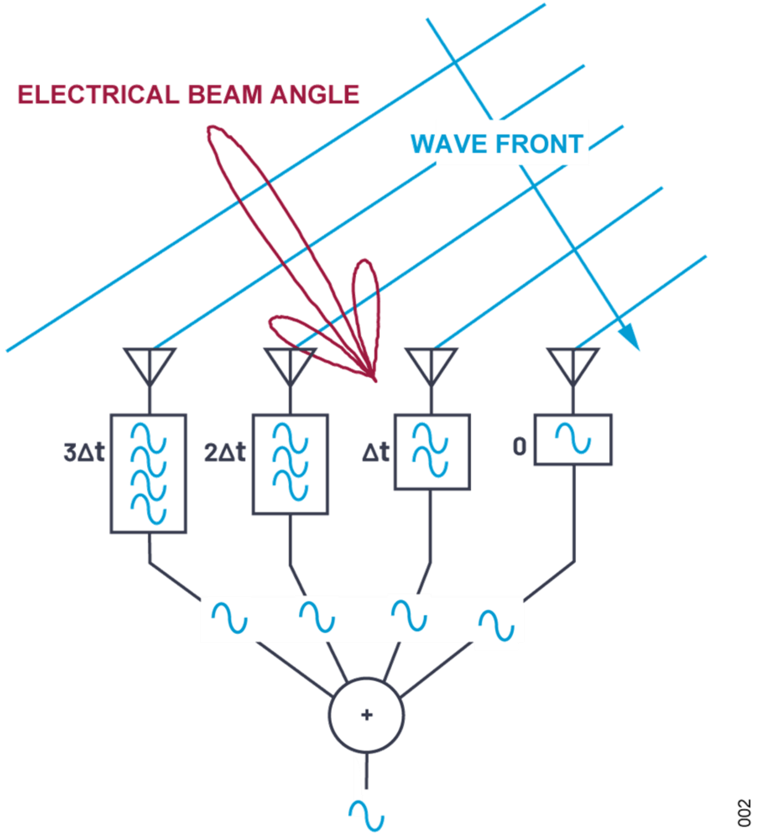
Arrays

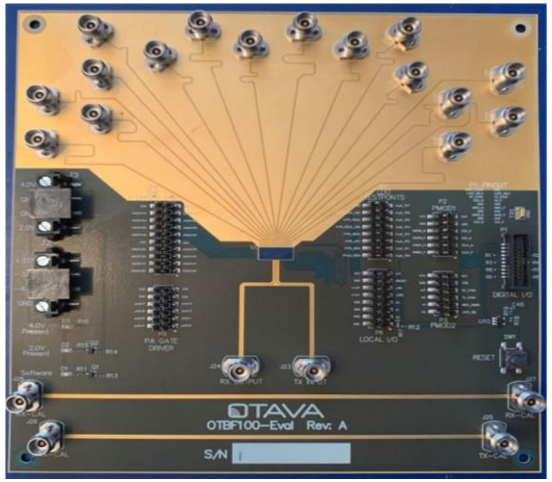
- More antennas combined to better resolution and sharper beam

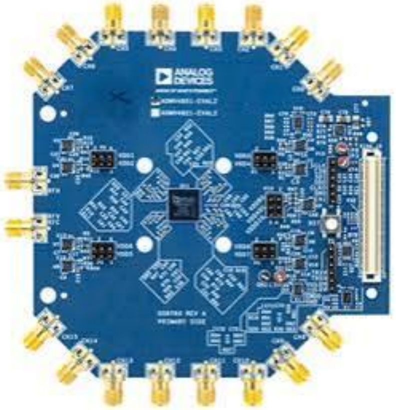


Phased Arrays and Beamforming Hardware

- Phase shifter and RF switch

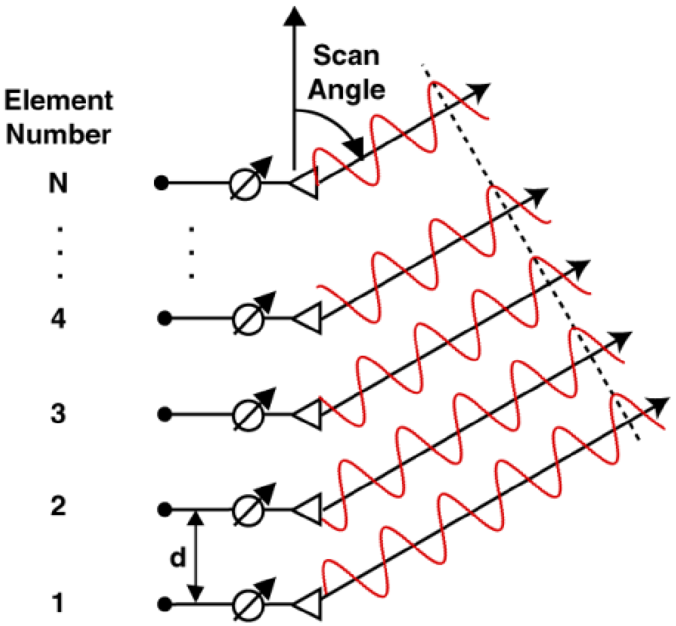






Phased Arrays and Beamforming Hardware

- Recap-phased array

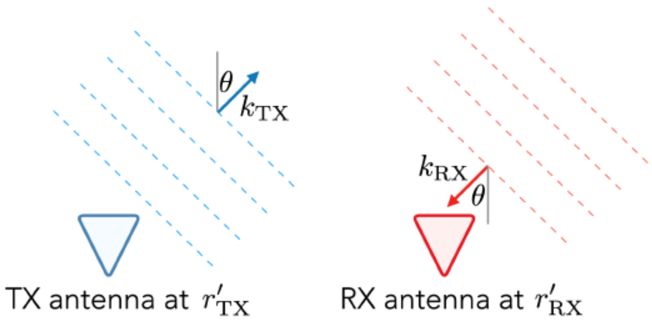


- DBF estimates DOA using the phase of signals from RX antennas
- Need a signal model to develop the DSP algorithms
- Assume a TX/RX antenna pair located at r'_{TX} and r'_{RX}
- Target in the far field at DOA angle θ
- Assume TX and RX fields are plane waves in opposite directions
- Electric field at the TX and RX antenna locations is given by:

$$E_{\mathrm{TX}}(r'_{\mathrm{TX}}, t) = e^{-jk_{\mathrm{TX}} \cdot r'_{\mathrm{TX}}} s_t(t)$$

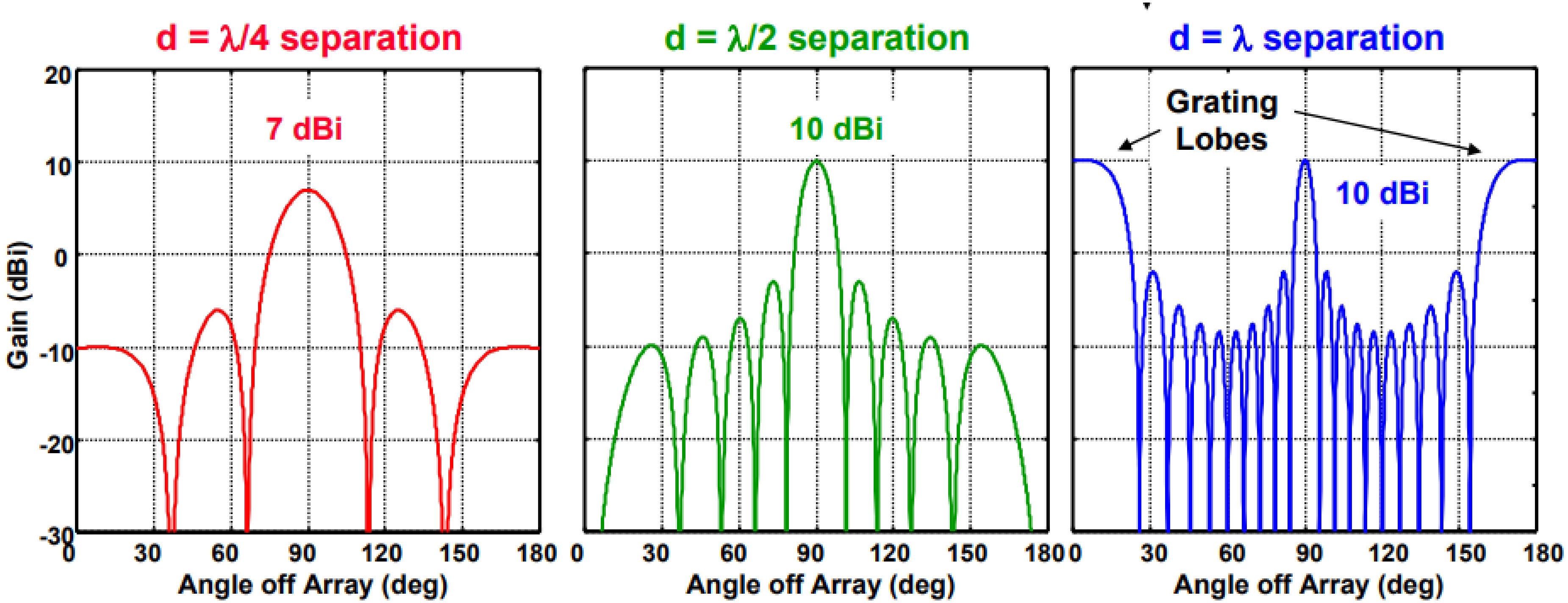
$$E_{\mathrm{RX}}(r'_{\mathrm{RX}}, t) = e^{-jk_{\mathrm{RX}} \cdot r'_{\mathrm{RX}}} s_r(t),$$

where $s_t(t)$ and $s_r(t)$ are the TX and RX waveforms, respectively

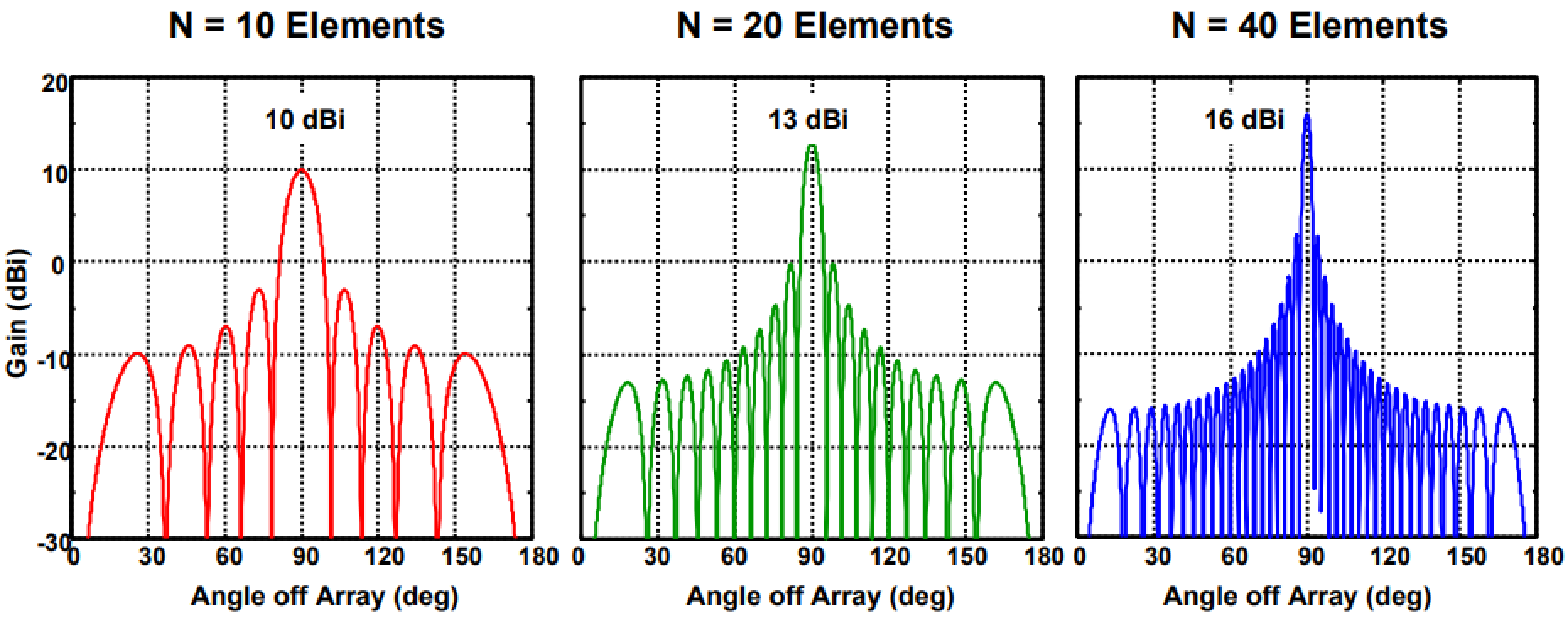


EE259 - Principles of Sensing for Autonomy   Direction of arrival (DOA) estimation   10

Array Size and Angular Resolution

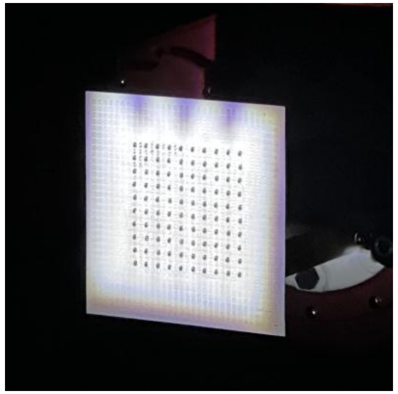


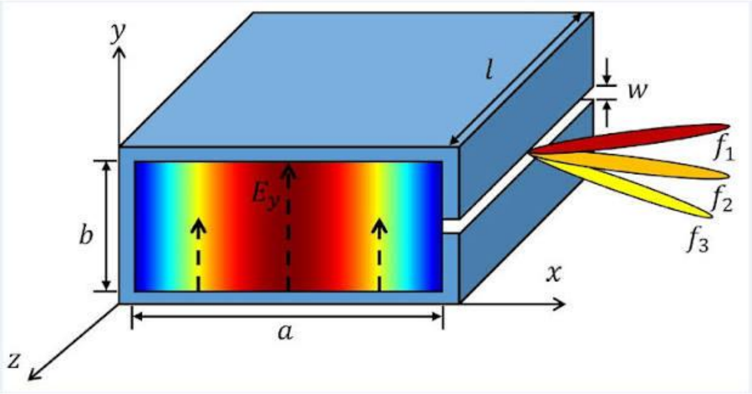
Array Size and Angular Resolution

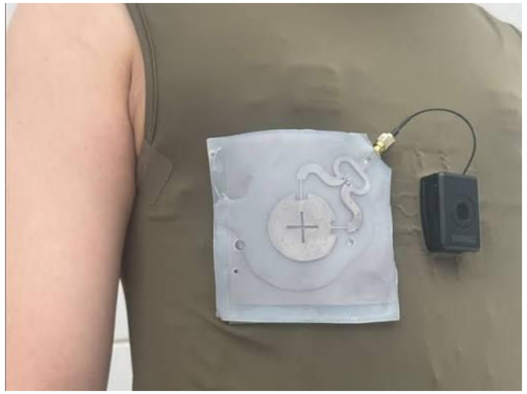


Research in Antenna

- New directions in
  - Dynamic Metasurface Antenna
  - Leaky-Wave Antenna
  - Wearable soft Antenna

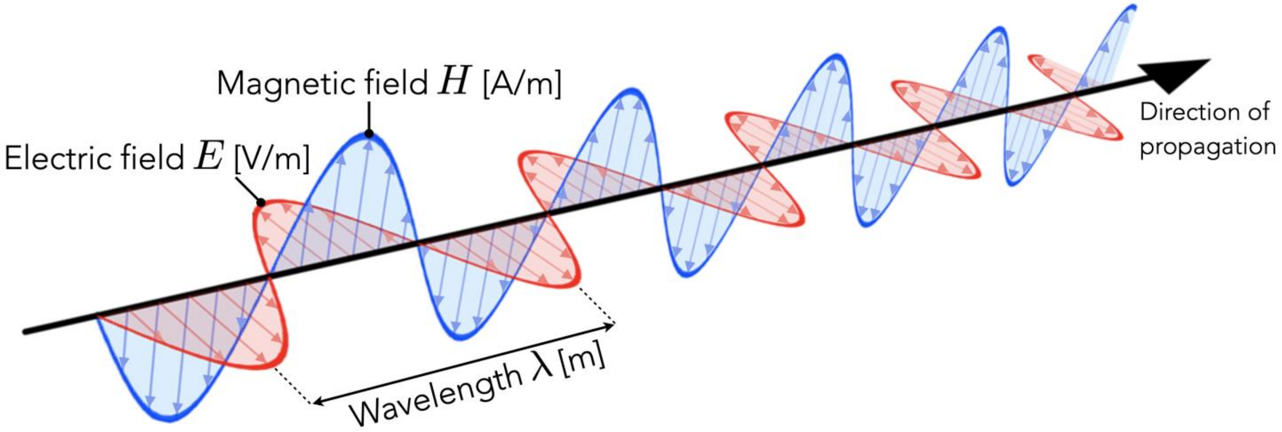


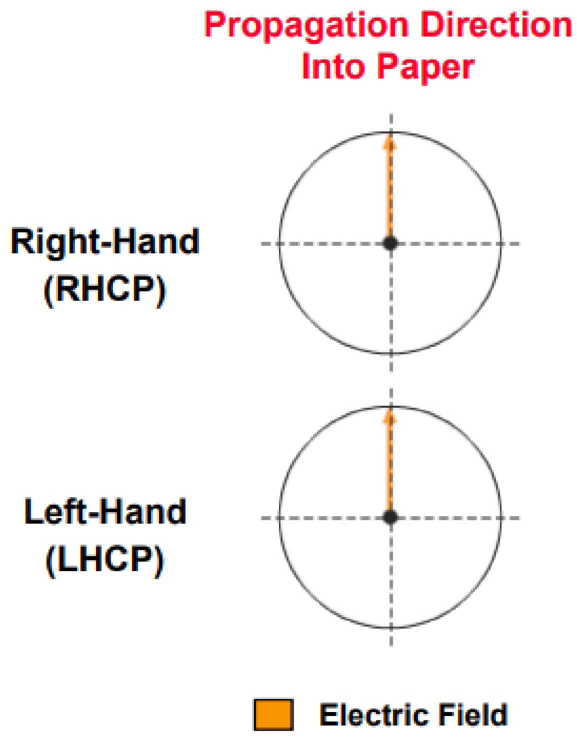




Polarization and Fields Regions

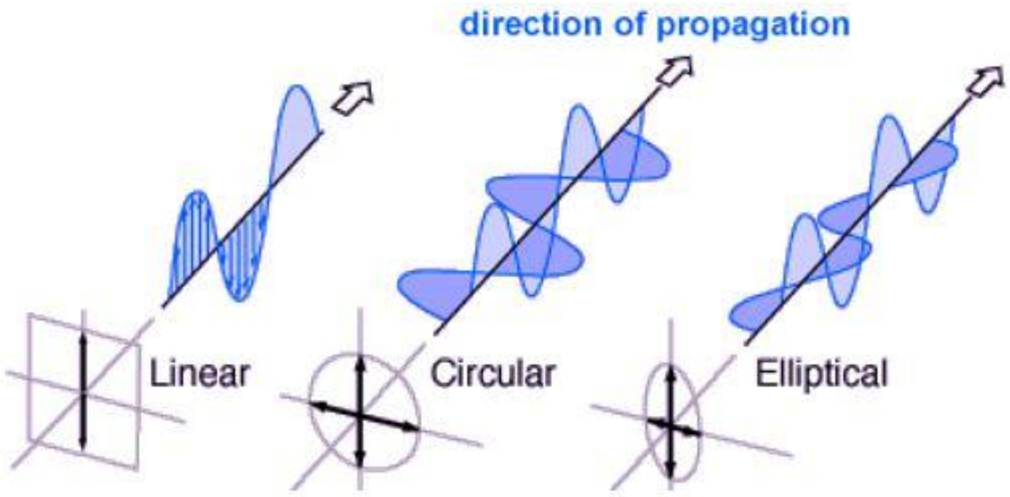
- "Handed-ness"
- Observation of electric field direction





Polarization matters

- Choose between **circularly polarized (CP)** or **linear polarization (LP)**



Polarization matters

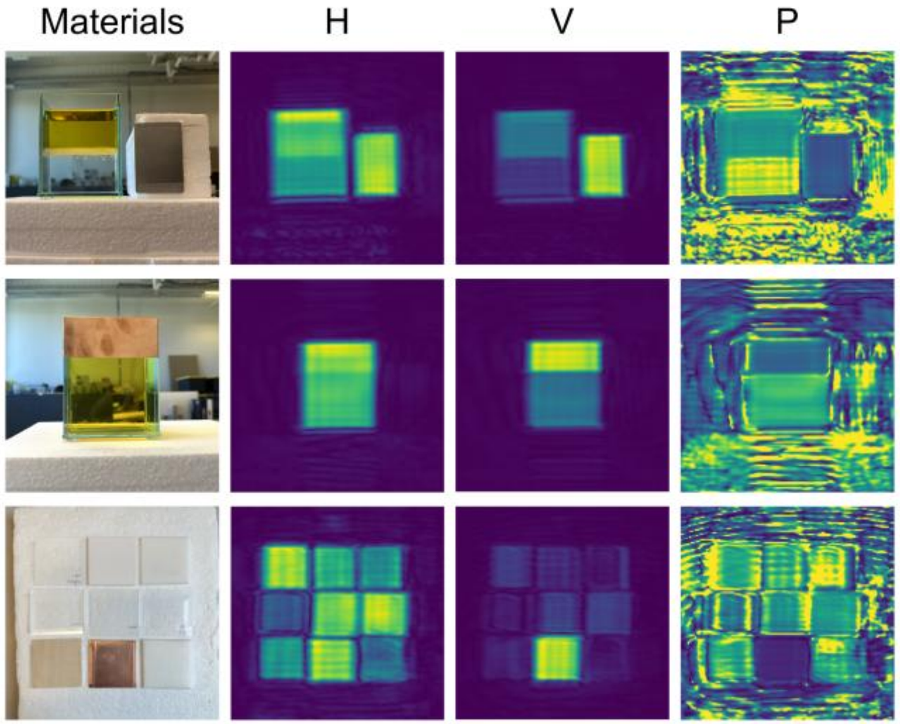
- Choose between **circularly polarized (CP)** or **linear polarization (LP)**

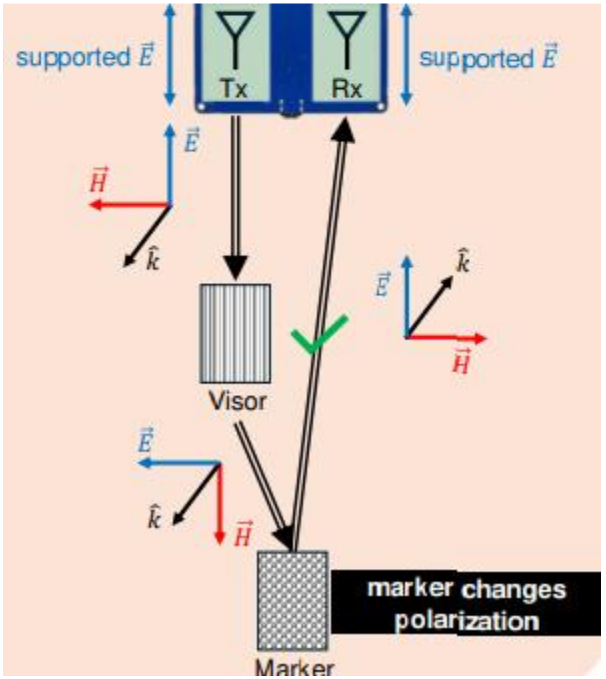
- **CP**
  - Right-hand (rotates clockwise) vs. Left-hand (rotates counter-clockwise)
  - Prevents signal loss due to multipath
  - Better resistant to interference

- **LP**
  - Electric field oscillates at an angle
  - Orientation sensitive
  - Special type is Slant Polarization in 45-degrees

Polarization Based Research System Design

- Radar measurements is sensitive to orientation [POLySight SenSys’26]
- Marker that only visible to radar in one orientation [PolarVisor Mobicom’25]





Polarization and Fields Regions

- Distance and power loss

Reactive Near-Field Region

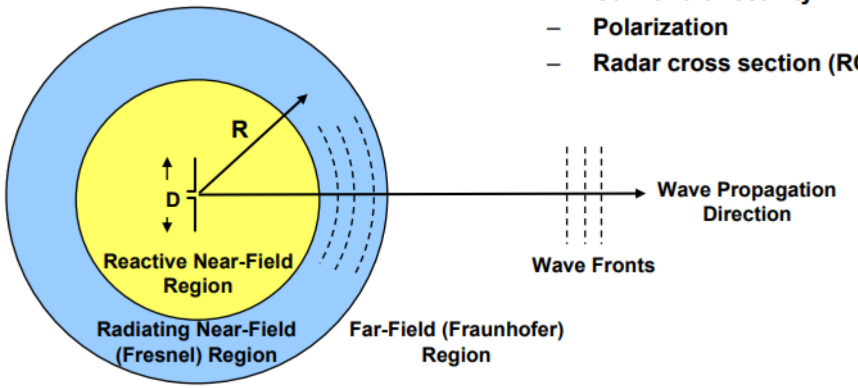
$$R < 0.62\sqrt{D^3/\lambda}$$

- Energy is stored in vicinity of antenna
- Near-field antenna quantities
  - Input impedance
  - Mutual coupling

Far-field (Fraunhofer) Region

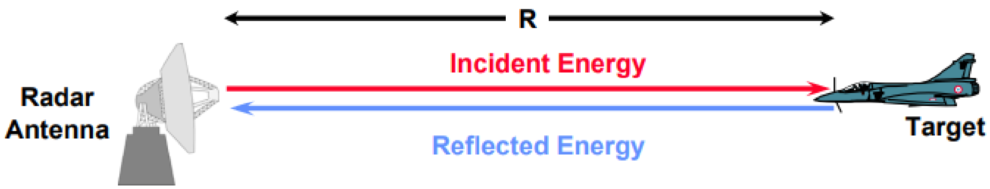
$$R > 2D^2/\lambda$$

- All power is radiated out
- Radiated wave is a plane wave
- Far-field antenna quantities
  - Pattern
  - Gain and directivity
  - Polarization
  - Radar cross section (RCS)



Target Radar Cross Section

- Recap



Radar Cross Section (RCS or σ) is a measure of the energy that a radar target intercepts and scatters back toward the radar

Power of reflected signal at target $\dfrac{P_t G_t \sigma}{4 \pi R^2}$

Power density of reflected signal at the radar $\dfrac{P_t G_t}{4 \pi R^2} \; \dfrac{\sigma}{4 \pi R^2}$

σ = radar cross section units (meters)^2

Power density of reflected signal falls off as ($1/R^2$)

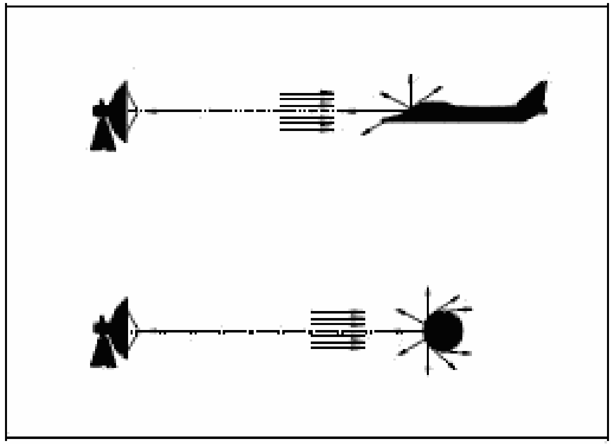
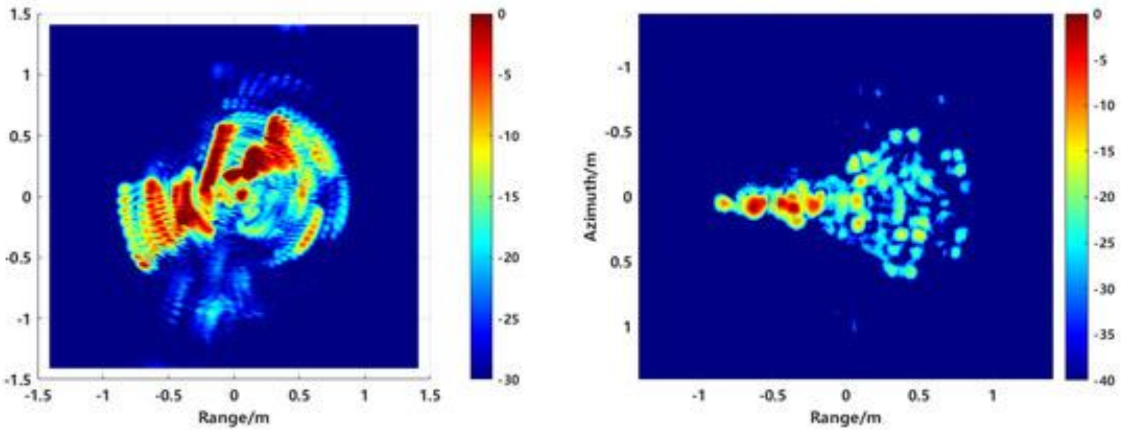


Figure 1. Concept of Radar Cross Section



(a) (b)

Propagation and Power Loss

- Recap – radar range equation

Power of reflected signal from target and received by radar

$$P_r = \frac{P_t G_t}{4 \pi R^2} \frac{\sigma A_e}{4 \pi R^2}$$

P_r = power received

A_e = effective area of receiving antenna

Propagation and Power Loss

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$

Why it matters? - The maximum detecting range

$$W_{\mathrm{r}} = \frac{P_{\mathrm{s}}}{4\pi R^2} = \frac{P_{\mathrm{TX}} G(\theta_t, \phi_t)\sigma}{(4\pi)^2 R^4} \quad (\mathrm{W/m^2})$$

$$R_{\max} = \left[\frac{P_{\mathrm{TX}} G^2(\theta_t, \phi_t)\lambda^2 \sigma L}{(4\pi)^3 P_{\mathrm{RX}}^{\min}}\right]^{\frac{1}{4}} \quad (\mathrm{m})$$

Constant False Alarm Rate Thresholding

- Problem: Must know (or estimate) noise floor to set threshold
- Solution: Estimate noise floor using noise
  - Adaptive thresholding
- CFAR thresholding
  - test cell / noise floor estimate > threshold

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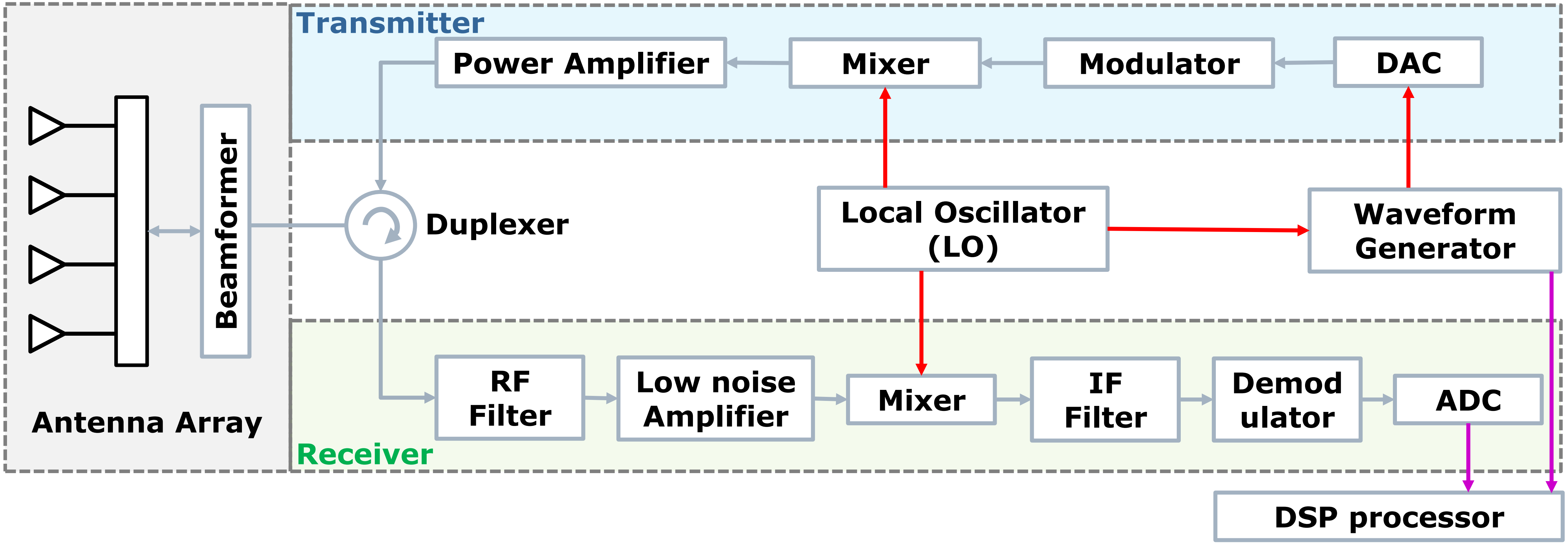
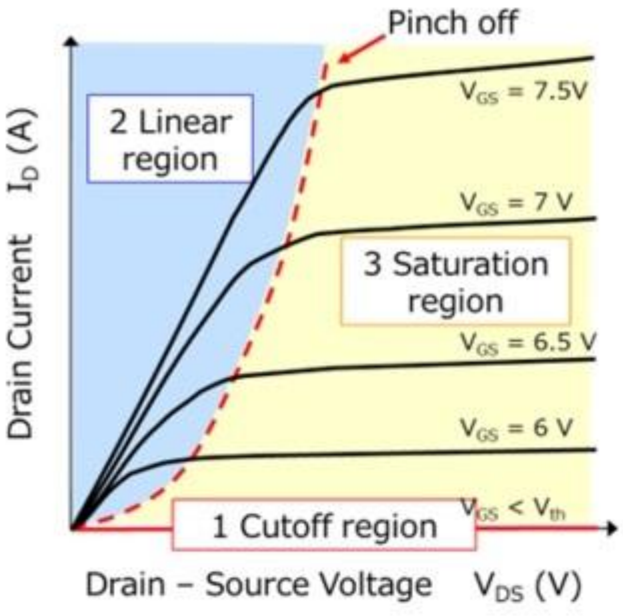
Radar Block Diagram

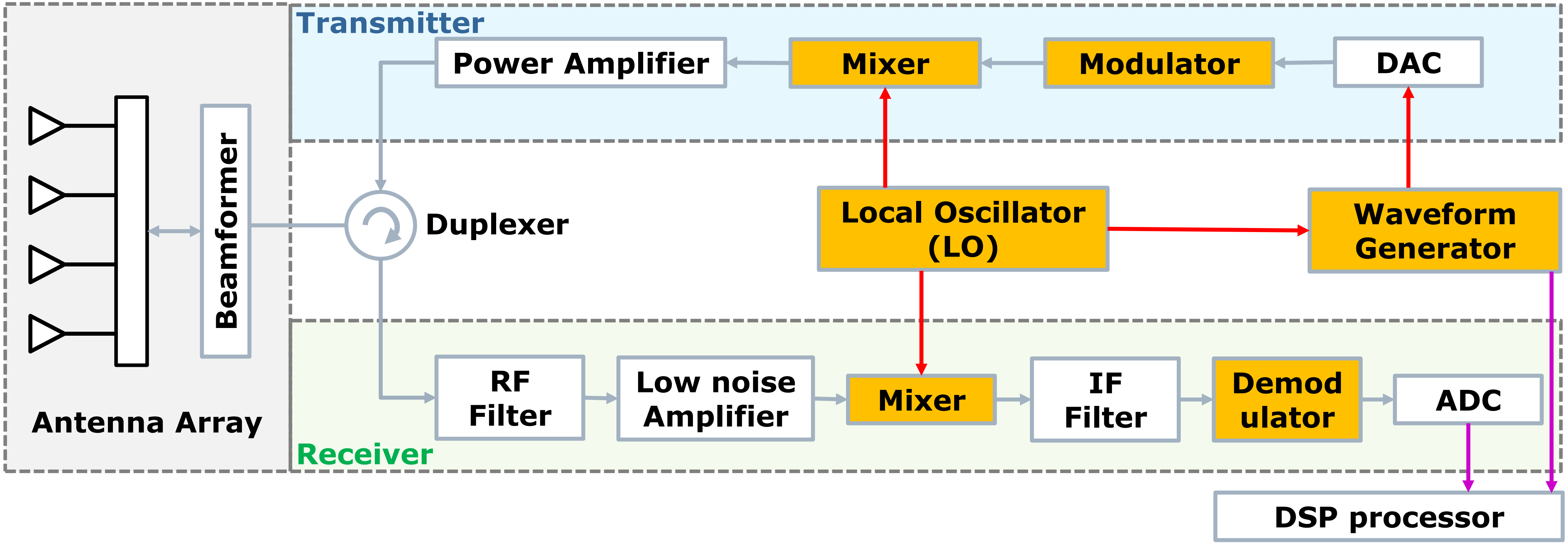


High-order Nonlinearity in Silicon

- **Harmonic distortion:** New signals at integer multiples of original frequency
- **Intermodulation distortion (IMD):** Mixes two or more signals together that jam nearby channels
- **Gain compression:** The output signal becomes weaker when the input gets too strong

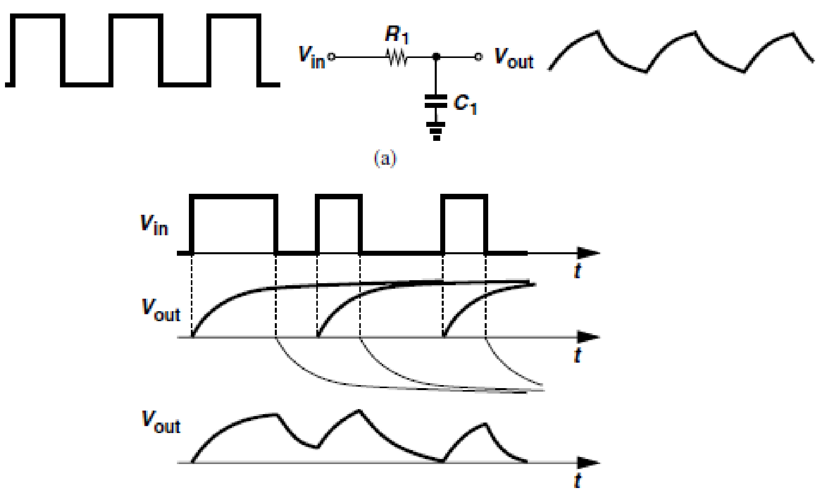


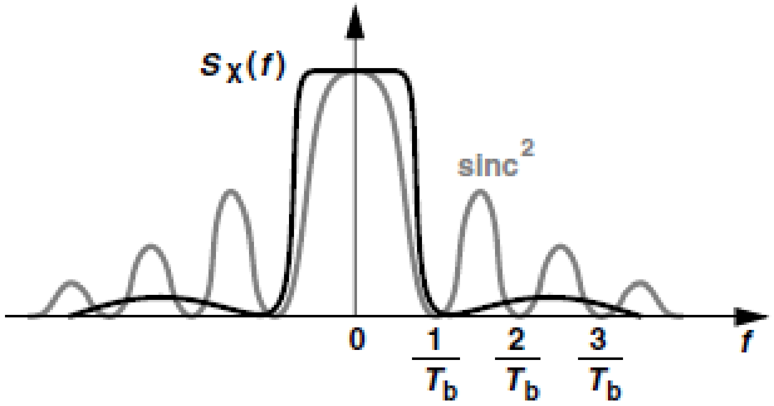
Radar Block Diagram



Modulation and Artifact profile

- Different artifacts based on modulation
- RF architecture introduces “noises” in both time and frequency
  - Time-limited pulse – Intersymbol Interference
  - Frequency spectrum is not perfect

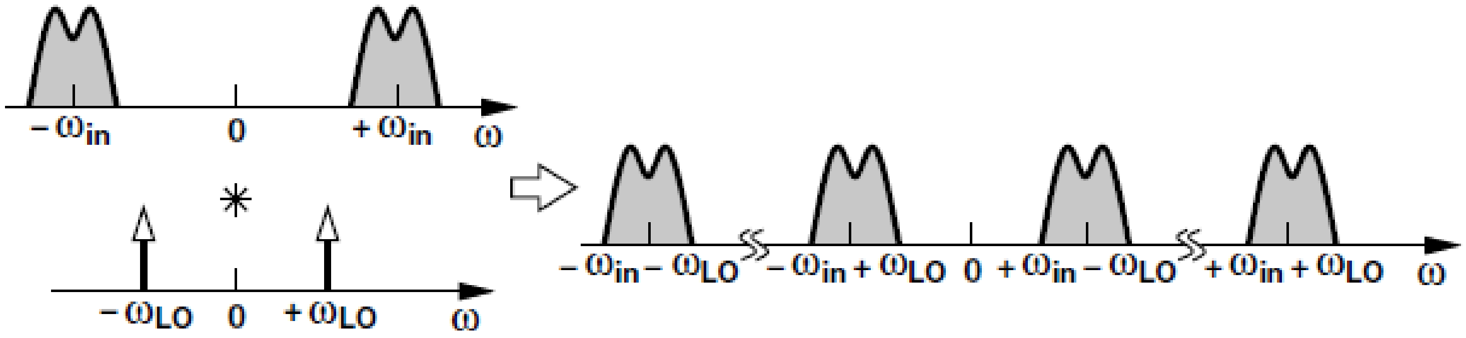




Mixer and LO artifacts

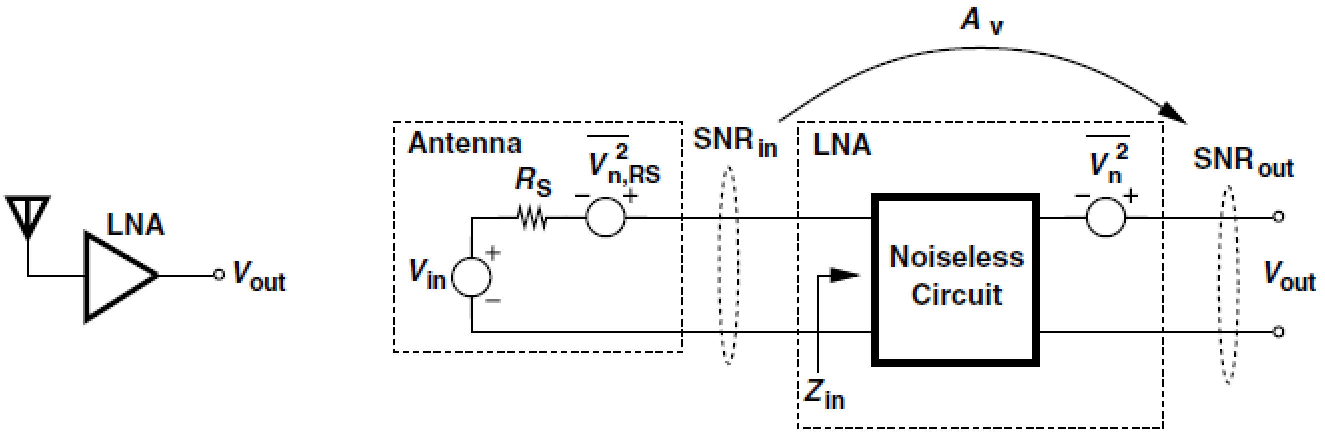
- Mixers translate the received RF signal to IF or baseband
- LO leakage creates unwanted harmonics
  - **Problem of Image – "image"** revealing that two spectra located *symmetrically*
  - Phase noise energy and spectrum

$$A\cos\omega_{IF}t = A\cos(\omega_{in} - \omega_{LO})t$$
$$= A\cos(\omega_{LO} - \omega_{in})t$$



Noise Figure and Sensitivity

- Receiver noise sets the weakest detectable target
- LNA noise figure strongly affects the receiver chain
- **Noise figure – defines the ratio of power (voltage squared)**
- Thermal noise power increases with bandwidth
  - N = kTB



(a) (b)

$$NF = \frac{SNR_{in}}{SNR_{out}}$$

$$NF|_{dB} = 10 \log \frac{SNR_{in}}{SNR_{out}}.$$

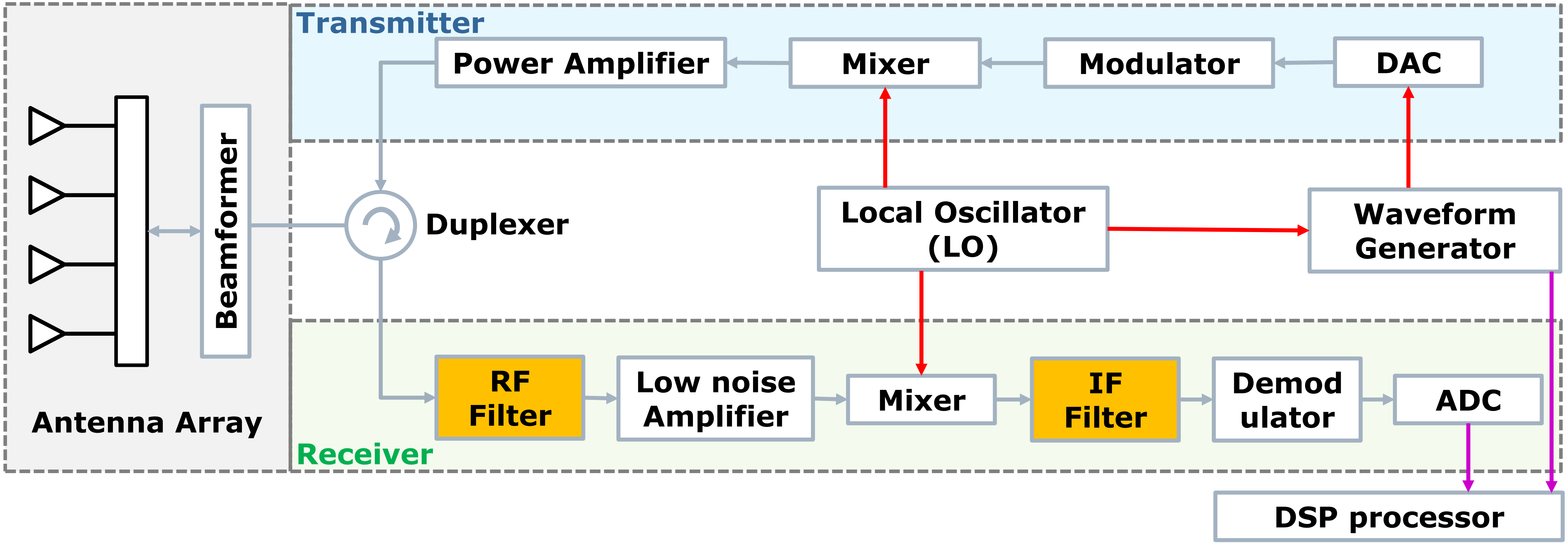
Overall Sensitivity

- The minimum signal level that a receiver can detect with “acceptable quality.”

$$NF = \frac{SNR_{in}}{SNR_{out}}$$
$$= \frac{P_{sig}/P_{RS}}{SNR_{out}},$$

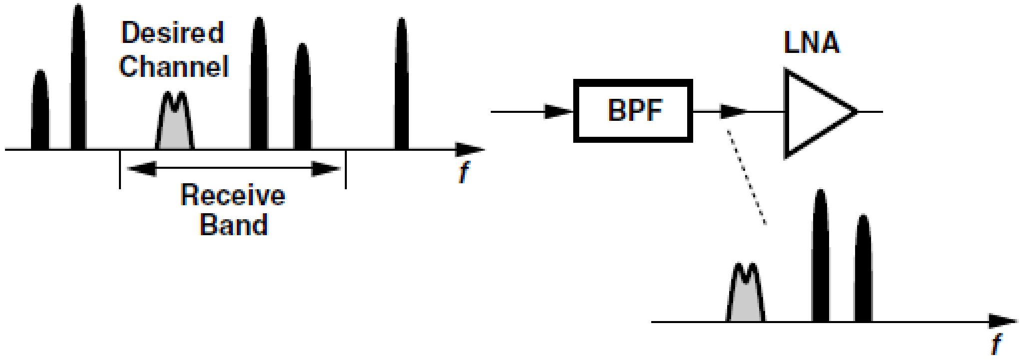
$$P_{sig} = P_{RS} \cdot NF \cdot SNR_{out}.$$

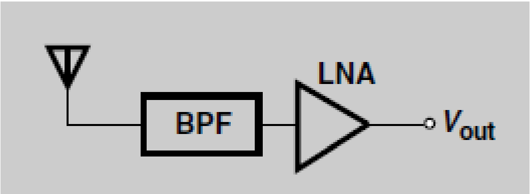
Radar Block Diagram



Filters

- Distinguish between out-of-band interferers and in-band interferers
- Also introduce noise!



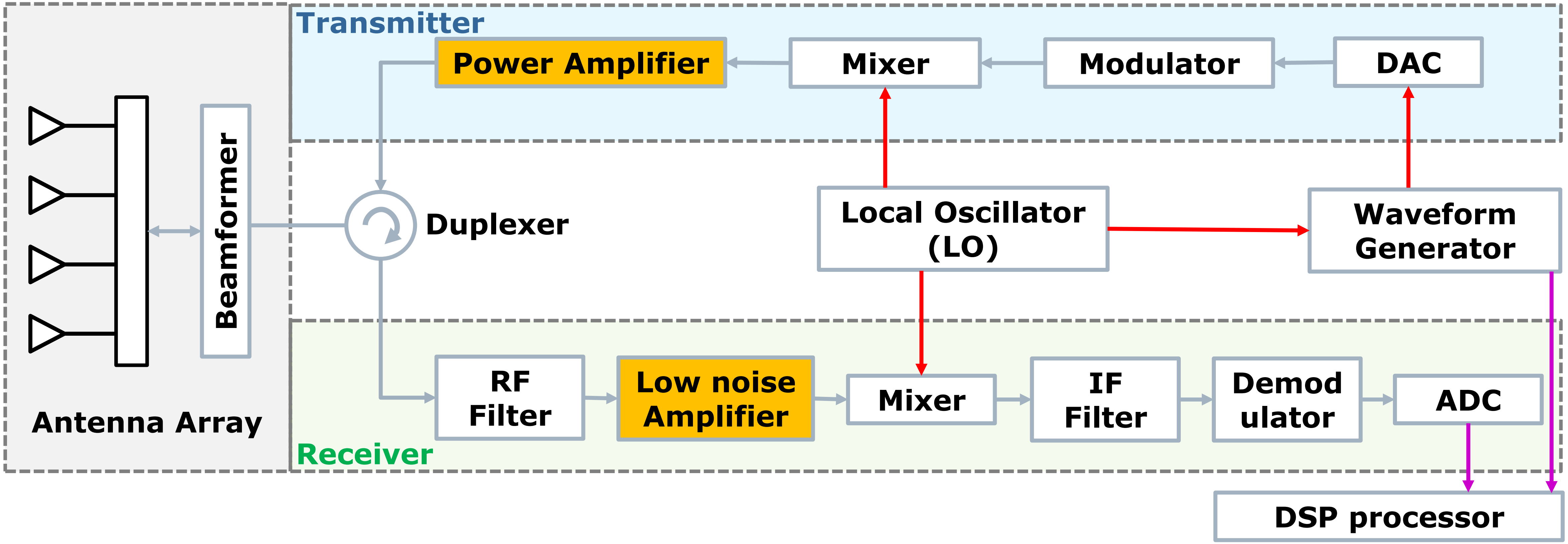


$$
\begin{aligned}
NF_{tot} &= NF_{filt} + \frac{NF_{LNA} - 1}{L^{-1}} \\
&= L + (NF_{LNA} - 1)L \\
&= L \cdot NF_{LNA},
\end{aligned}
$$

Cascade Filters based on Design

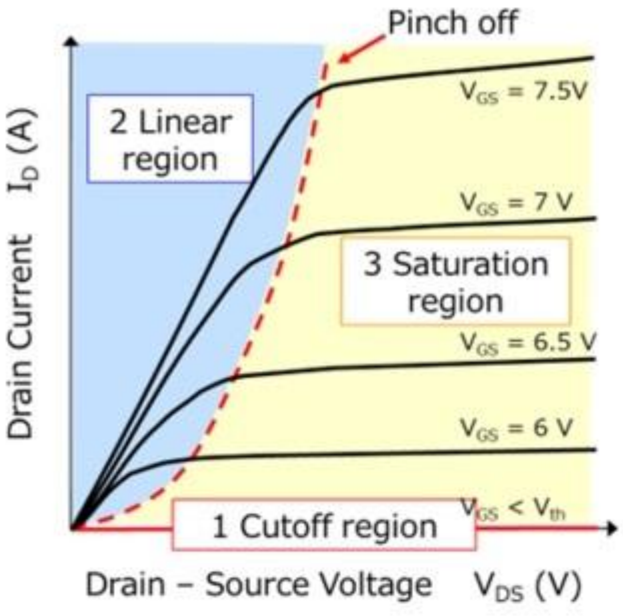
- RF filter – select desired RF band and reject the others
- IF filter – choose the correct beat frequency after mixing
  - Remove images

Radar Block Diagram



Which part is nonlinear?

- Frequency dependent?
- Or Waveform dependent (transient)?



Which part is nonlinear?

- Frequency dependent?
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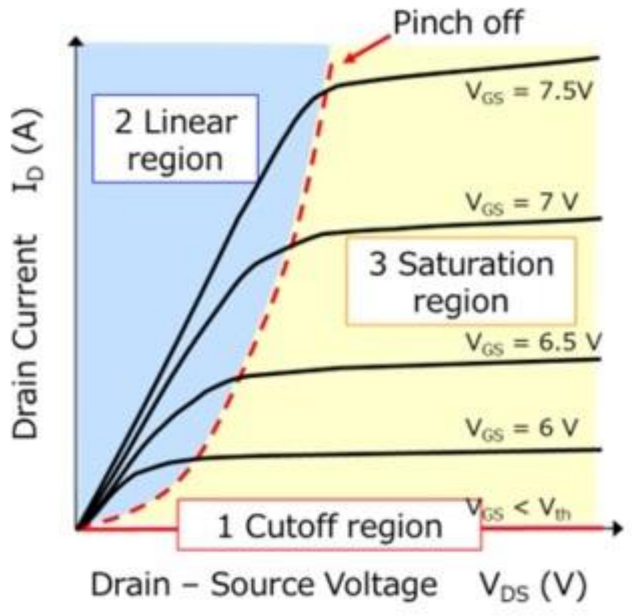


Nonlinearity in RF Components

- Nonlinear input-output behavior
- Large signals create harmonics and intermodulation products
- Gain compression reduces amplitude accuracy
- **Harmonic distortions**

$$y(t) = \alpha_0 + \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \cdots,$$

Harmonic Distortion

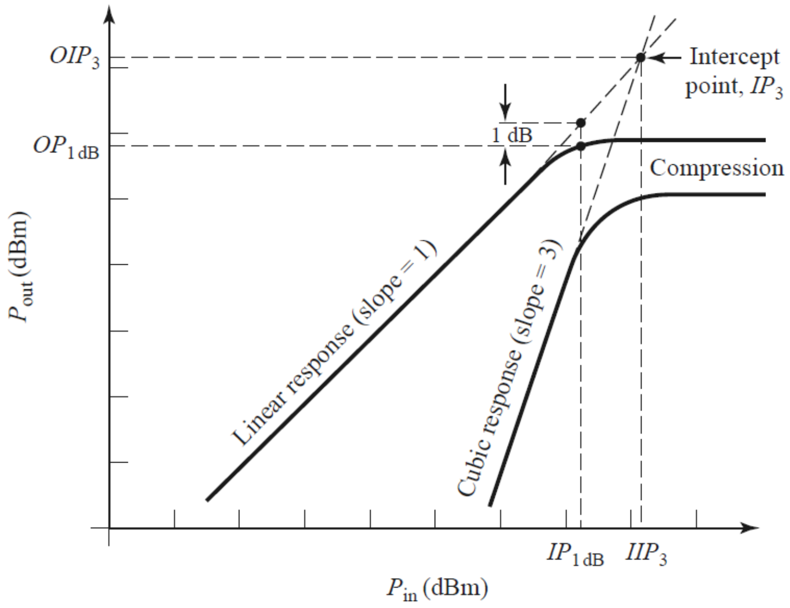
- Frequency components with integer multiples of input frequency

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$$

$$\begin{aligned} y(t) &= \alpha_1 A \cos \omega t + \alpha_2 A^2 \cos^2 \omega t + \alpha_3 A^3 \cos^3 \omega t \\ &= \alpha_1 A \cos \omega t + \frac{\alpha_2 A^2}{2}(1 + \cos 2\omega t) + \frac{\alpha_3 A^3}{4}(3 \cos \omega t + \cos 3\omega t) \\ &= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right) \cos \omega t + \frac{\alpha_2 A^2}{2} \cos 2\omega t + \frac{\alpha_3 A^3}{4} \cos 3\omega t \end{aligned}$$

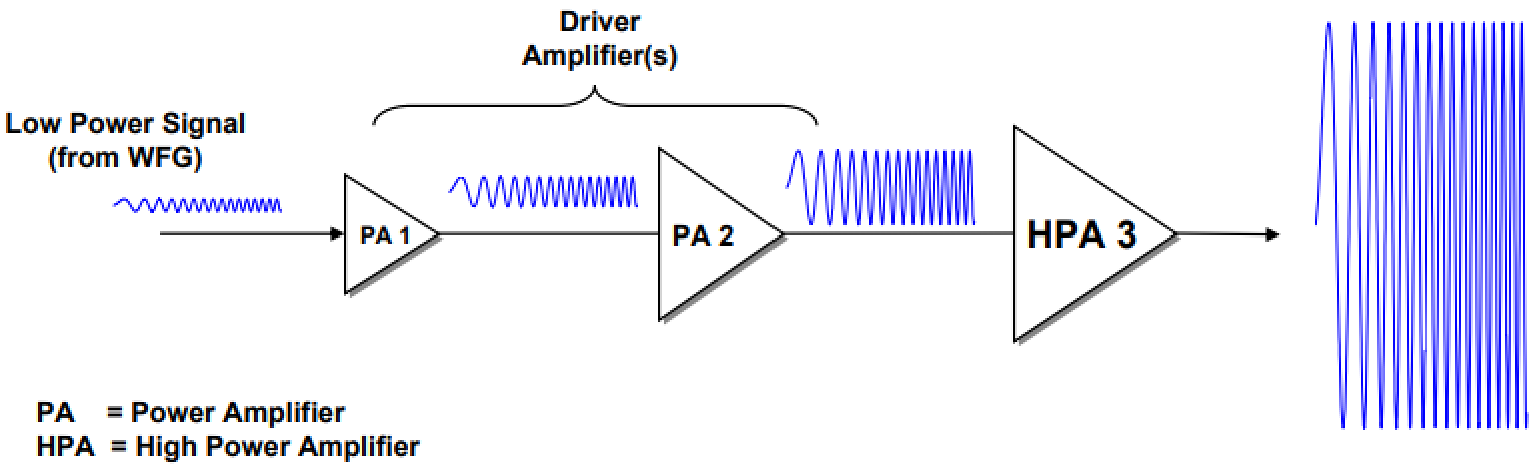
Third-Order Intermodulation and IP3

- Third-order products are harmful because they fall near the desired band
  - 2f1 – f2 and 2f2 – f1
- IP3 estimates how quickly third-order distortion grows
- Higher IP3 means good linearity and less signal distortions

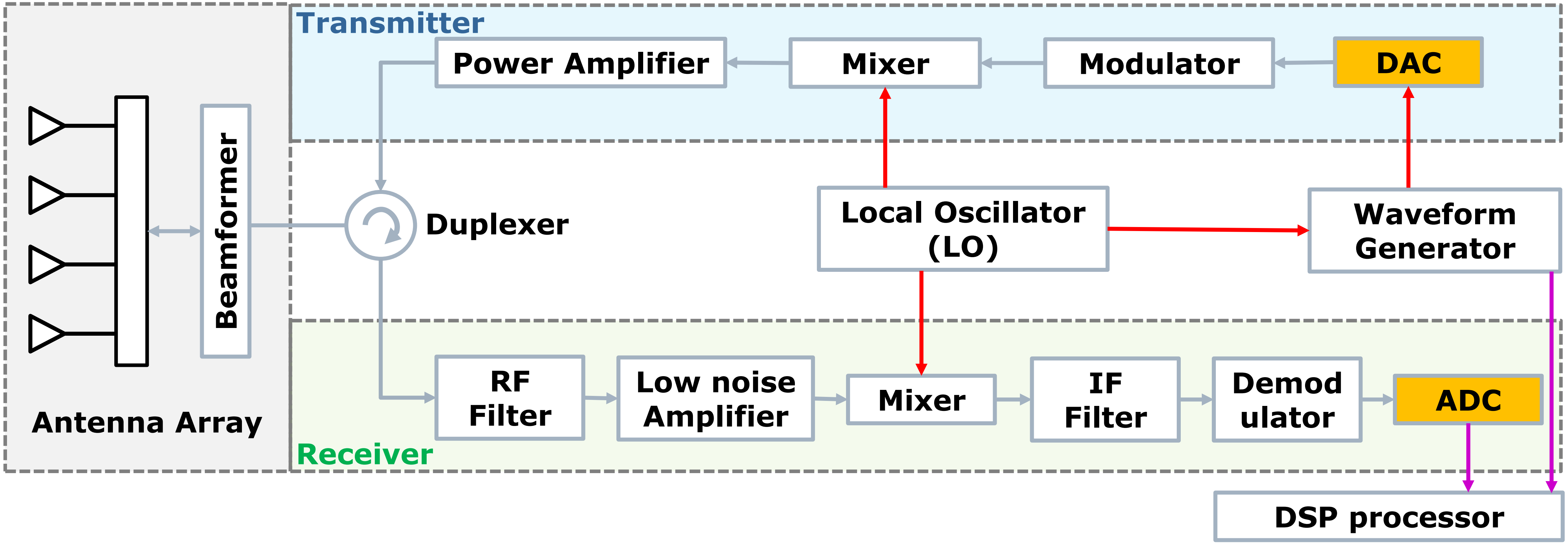


Why cannot we chain a lot of amplifiers?

- Noise will accumulate
- Distortion will also be amplified
- Stability and bandwidth shrinks fast

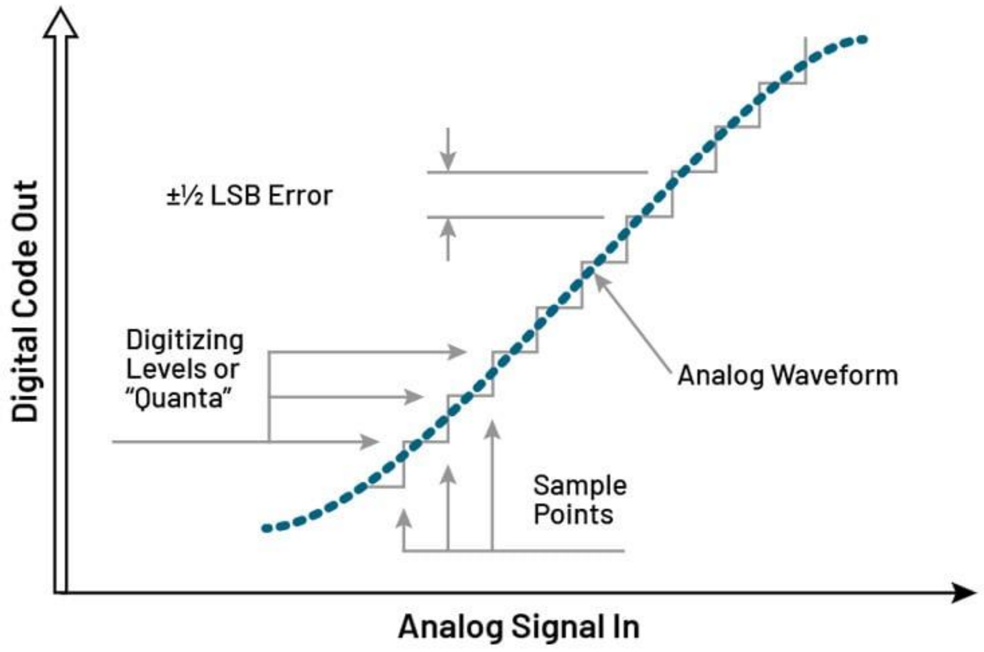


Radar Block Diagram



Sampling and Quantization

- ADC sampling rate must **cover the IF bandwidth**
  - Insufficient sampling causes aliasing and false frequency content
  - Effective number of bits, ENOB compresses noise and distortion as one number



Other factors?

Transceiver Architecture Design

- **Which architecture to use?**
  - Heterodyne Transmitter/Receiver
  - Direct-Conversion (Zero-IF) Transmitter/Receiver
  - Image-reject Receiver
  - Low-IF Receiver
  - Sliding-IF Transmitter
- Typical FMCW radar is **Direct-Conversion (Zero-IF) Receiver**
  - TX and RX chirps are mixed directly to get beat frequency

$$s_{\mathrm{TX}}(t) = \cos(2\pi[f_0 t + \tfrac{1}{2} S t^2])$$

$$s_{\mathrm{RX}}(t) \approx \cos(2\pi[f_0 (t-\tau) + \tfrac{1}{2} S (t-\tau)^2])$$

Modulation and Artifact profile

- Harmonics occur at integer multiples of the original frequency
- For chirps, harmonics create extra chirp-like components

Outline

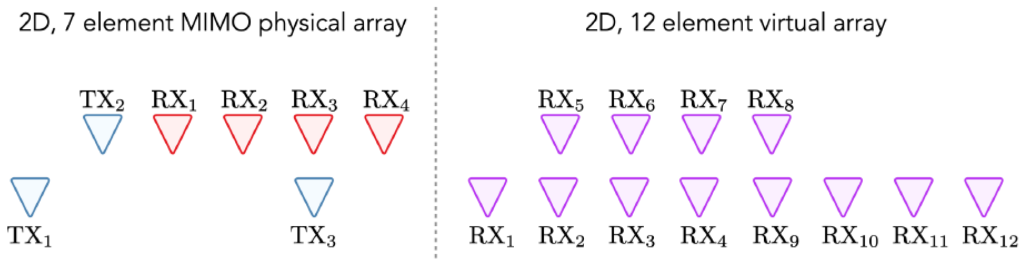
- RF hardware architecture
- Radar block diagram
- Fundamental antenna concepts
- Phased array antennas
- Power, noise and compression
- Next – How to pick the correct radar module?

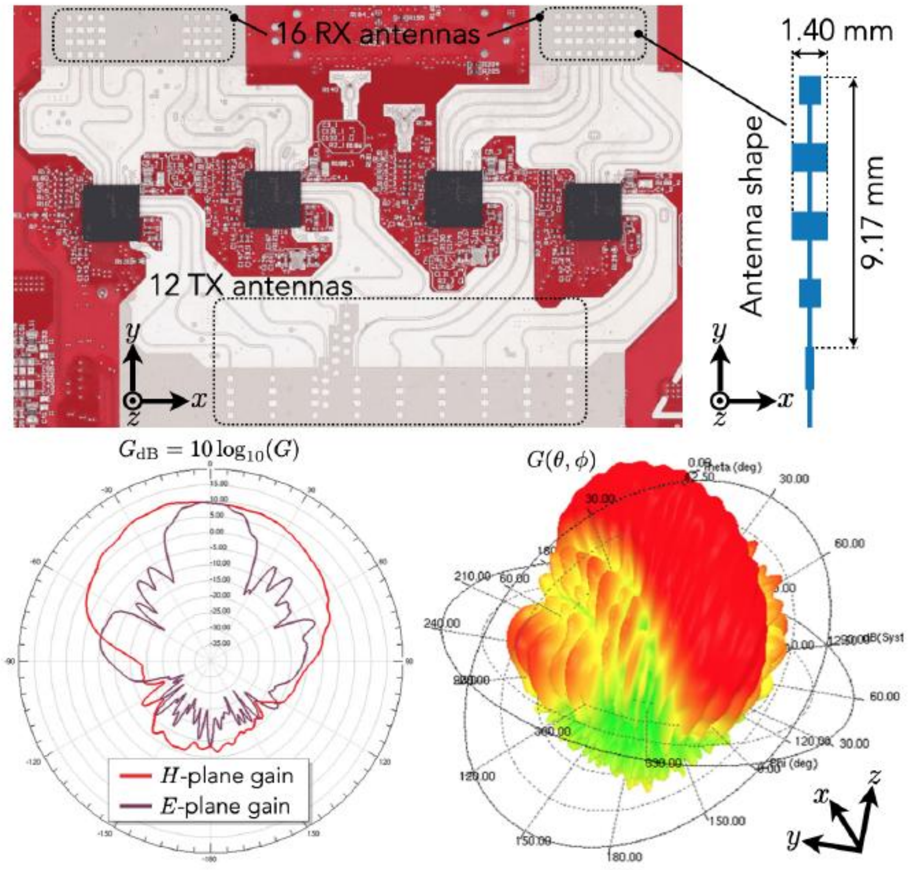
Setup and Choosing Components

- Radar receivers must handle strong leakage and weak
- Dynamic range links noise figure, gain, linearity, and ADC resolution
- FMCW radar is sensitive to phase noise, chirp nonlinearity, and leakage

Walk-through example – TI Radar modules

- Target DOA is determined by azimuth and elevation angles (θ, ϕ)
- Need a 2D virtual array to estimate both θ and ϕ
- Since θ and ϕ can be estimated independently, we consider $1D$ virtual arrays and estimate θ only to simplify the notation





Credit: Texas Instruments

Main Reference

- MIT Lincoln Laboratory Radar Course
- "RF Microelectronics," by Behzad Razavi, 2nd Edition